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Engine Life Extension through the Use of Structural Assessment, Non-Destructive Inspection, and Material Characterization

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Abstract

For over twenty years, the USAF has had a life extension program for major rotating hardware, such as rotors, seals, and shafts. This program was called Retirement-For-Cause (RFC). Damage tolerance philosophies are essential to this lifing technique. Damage tolerance has been applied to all new engine programs as part of the Engine structural Integrity Program (ENSIP) within the USAF since 1984. An essential element of ENSIP and RFC is non-destructive evaluation (NDE). Not only is there a need for NDE equipment, but also the quantification of the NDE system/process. The RFC program provided state of the art NDE equipment and software to enable complex inspections. Due to these advancements low cycle fatigue no longer needs to be the governing factor in the retirement of engine hardware from service when you have a fracture control program. The process of fracture control or damage tolerance as it is also called governs the selection of material as well as the design and life management of the engine. Recent USAF experience clearly demonstrates that the damage tolerance philosophy has had a positive effect on safety within the design life and has shown with our limited experience in RFC that safety is maintained and it is cost effective when assessed on a life cycle cost basis. The initial RFC program had some problems and it is imperative for any future programs that we don't repeat those same mistakes. In order to make life extension of hardware more robust and more cost effective, a new program has been developed called the Engine Rotor Life Extension (ERLE) program. This paper will discuss the original RFC program and its shortcomings as well as our future needs.

Introduction

The problems with rising costs today are worse than they were 20 years ago. We were just anticipating having a few engines reaching their design life. Today the majority of the fleet are nearing retirement based on LCF, yet we still have a desire to lower our operational costs. The answer to this dilemma is to extend the life of our major rotating hardware. This is where the majority of the cost of the engine resides. This need is the same today as it was for the original RFC program. As always, in order to accomplish this task, it is necessary to use innovative lifing techniques, which can reduce the conservatism achieved through our analysis, while maintaining equivalent or even lower risk. In order to understand the magnitude of this problem we need to view Figure 1., which shows the breakdown by engine model of the replacement cost for rotors to be inducted over the next 10 years.

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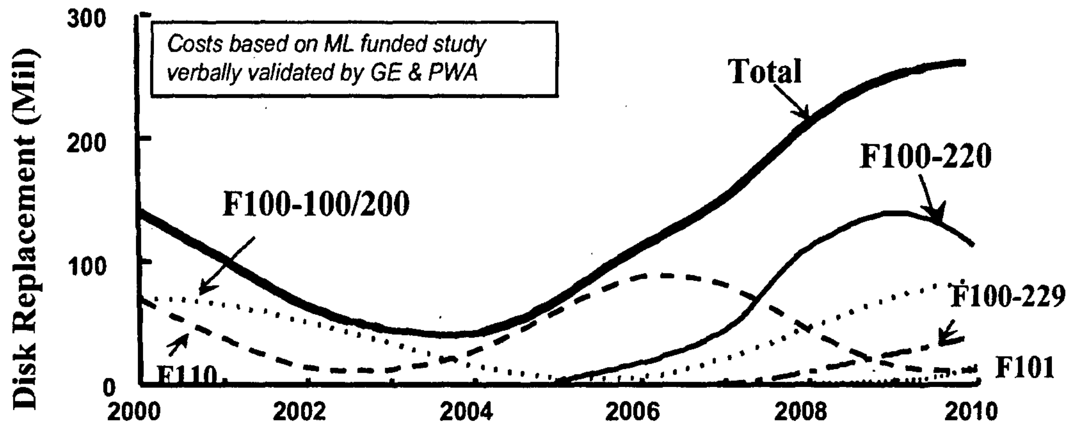

Figure 1. Future Disk Replacements

Figure 2. shows our anticipated savings based on implementing current technology and also if we have added technology investment. These replacement disk savings are based on the numbers of disk generations in Figure 1. As can be seen the savings are well worth the time and effort to achieve these goals. As also can be seen it is imperative to go after technology investment. We can more than double our savings by adding a small investment now.

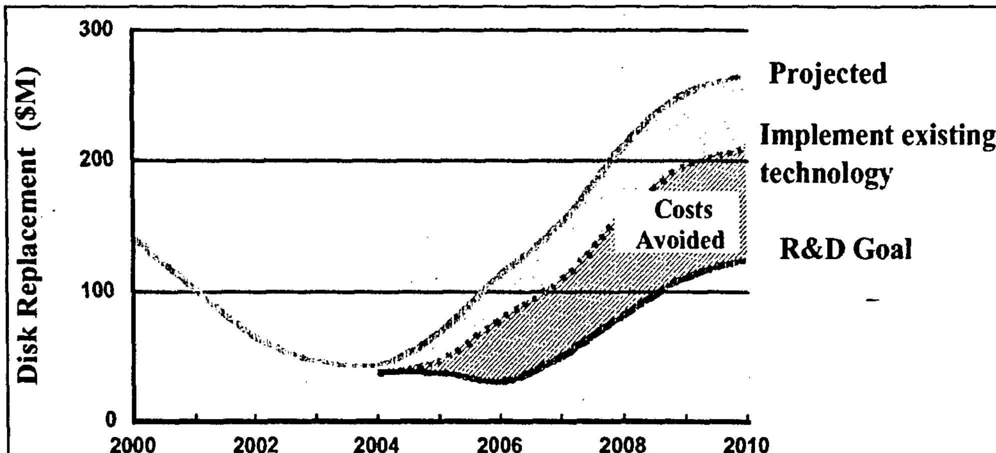

Figure 2. RFC Projected Savings

USAF Lifing Methodology

To help understand these savings, first I believe it is necessary to understand the standard USAF lifing methodology. The program is referred to as the Engine Structural Integrity Program (ENSIP). This program is more than just lifing, but for purposes of this paper we will only talk about the lifing and inspection areas of the program. The retirement life for hardware is the -3σ or equivalent life to crack initiation (defined as a 1/32 of an inch crack). Inspection intervals are based on ½ the average crack growth life from an inspectable flaw size to dysfunction. This inspection interval is termed the safety inspection. No credits are given for shot peening or other surface treatments, which can retard crack initiation, unless a full material characterization program shows a change to the -3σ material curves. This has seldom been done in the case of shot peening due to the variability in the processing. This results in a substantial increase in mean material properties, but an insignificant change in the minimum properties. As one can see, by using minimum material properties and allowing no credits this lifing method is conservative in nature. Unfortunately we can no longer afford to sustain this conservatism. Aircraft fleets are aging and yet, we need to keep that hardware usable and maintain safety of the fleet. The purchase of replacement engines has not been accounted for in our maintenance planning.

RFC was a program developed in the early 1980's. The theory behind this program was based on damage tolerance. We would continue to inspect hardware until we found a crack with our NDE techniques. A risk management program called the probabilistic life assessment program (PLAP) was developed (later changed to PLAT). This program would enable the assessment of the risk of achieving the next interval based on the FEM analysis, the inspection areas, and the inspection reliability. It took many years to develop the inspection equipment necessary to find the small flaws at the necessary reliabilities. The F100-PW-100/200/220 engines have used RFC, but not as it was fully intended and thus the predicted savings have not been achieved. The reasons for this are many. First and foremost was a change in flight missions for our aircraft. This change in mission reduced the LCF and fracture life of the hardware. These shortened lives prohibited the use of RFC for many of the anticipated hardware due to increased (unacceptable) risk. As with any lifing technique it is essential to have FEM analysis based on real updated mission usage. Thus, periodically there must be provisions for analysis updates due to mission usage changes. Second, it is imperative that maintainers understand that RFC inspections are different than normal safety inspections. Once you have reached the minimum LCF life, there will be more areas that need inspection to go on beyond this quoted life in order to maintain the same risk as in the first lifetime. This is not limited to surface inspections. When a rotor is first manufactured, it is sonic inspected for imbedded defects which would prohibit the rotor from making its' minimum life. This type of inspection (ultrasonic) would need to be done. However, we are no longer concerned with small void type defects, but with the cracks that would emanate from those defects. This requires sophisticated sonic equipment that can find the crack edges reliably. In the 1980s both Eddy Current (EC) and ultrasonic inspection systems were developed by Systems Research Laboratory for the USAF RFC program. These systems were put in place at the San Antonio - Air Logistics Center. The EC systems were used for safety limit inspections prior to true RFC use. Because of the misunderstanding about required inspections, the required analysis and inspection scan plan generation was not put in the funding cycle. Because of both the mission change and the delay in analysis required to extend the life with RFC, only limited hardware actually was extended, and then for only one interval. Thirdly, material characterization must be full and complete even on old/used material. This is necessary for crack growth data as well as stress rupture, and other strength characteristics. This also was not done and hence the lack of ability to extend the life intervals.

Revitalization of the RFC Methodology

In an effort to revitalize RFC. A new program called Engine Rotor Life Extension (ERLE) is being developed. It is intended to correct the shortcomings of the old RFC program. Enhanced inspection equipment are being developed. This includes a replacement system for the RFC ultrasonic system that was dismantled due to non-use. This system is anticipated to also be able to detect cracks emanating from acceptable defects in the normal forging process. Figure 3 below shows the ENSIP approach as well as the RFC process.

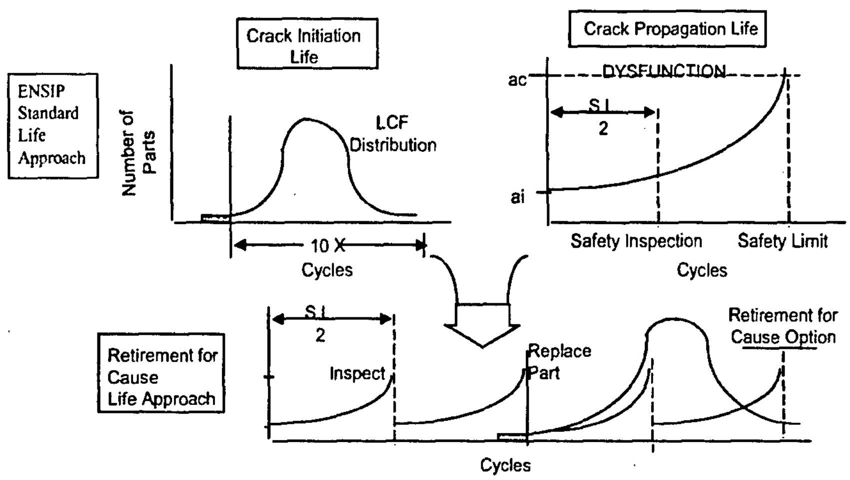

Figure 3. ENSIP Lifing and RFC

Both the RFC program and the ERLE program rely on the same theory. The USAF lifing methodology retires 999 good rotors when only one is bad. It is a simple matter to just keep the hardware in the fleet longer, but our customers and we, ourselves, have become accustomed to a certain level of risk. In order to keep that inherent risk level; we need to think about managing our inspection intervals differently. As more and more hardware is kept in the system the inherent risk goes up if nothing else is changed. However, it is possible to maintain the same risk by lowering the inspection interval. This requires a flexible tracking and Life Management system. Consider the following example: A high pressure turbine disk has a standard ENSIP LCF life of 9000 Total Accumulated Cycles (TACs) and an inspection interval based on fracture mechanics of 4500 TACs. The disk is inspected at half-life and returned to service. At 9000 TACs it would be retired under the standard system, but under the RFC program it would continue in service. However, to continue, one must look at all areas of the disk analytically. Suppose the bolt hole area had a fracture inspection interval of 10000 TACs. In its original life, it would not have needed to be inspected. Now for RFC we must develop an inspection technique and inspect that area. Suppose also that the imbedded defect life was exactly 9000 TACs. We now also need to re-ultrasonic inspect the disk, but looking for cracks not just the normal imbedded defects. As we keep doing this we find more and more areas that need to be inspected and the risk of having the original areas crack are becoming greater. Thus we need to alter the inspection interval to do this. The PLAT software program is a probabilistic life assessment tool designed to assess both risk and the areas needing inspection. The use of PLAT can help determine the useful life. It needs to be updated as well.

Even though we advocate RFC, the question becomes; "What is cause?" "Cause" can be based on inspection findings, unacceptable risk, or even economics. Consider the following example: A rotor stage has been extended 2 intervals. On inspection for a 3rd interval, 50 % of

the rotors are rejected due to inspection findings. At this point, if the cost of the inspections is equal to or greater than the cost of rotor replacement, it would be best to retire all the disks after the 2nd interval for economic reasons.

Other ways to take conservatism out of analysis is to allow credit for beneficial stress that limits the ability of the part to initiate a crack. Compressive residual stress imparted by peening and cold working processes has not been allowed due to variability in the process and the inability to reliably use non-destructive inspection to verify the beneficial compressive residual stress. A new x-ray diffraction technique has now made the inspection possible. This will assist in management of fleet assets and add a measure of safety by finding below average disks ***before*** they crack, thus avoiding field problems. This new technique for tracking turbine engine component life may offer improvements to the engine life management tracking process, thus providing the customer with a more affordable and reliable system. The improvements will result from several factors, including full utilization of engine disk design life, life management on a module or component basis, improved system safety, and reduced spare parts requirements. The new life tracking technique employs technology that relates engine cycles to increments of disk life. This new approach uses residual stress to quantify engine disk life and compares each disk with other disks that make up that family database by alloy. At each subsequent inspection interval, new residual stress measurements will be made and this accumulated historical data will provide a realistic determination of which disks can safely reach full life and which disks should be retired at some earlier interval.

This new residual stress measurement technology is not intended to replace other NDT techniques such as EC crack detection inspections. It is, however, recommended that this technology be used as an inspection to complement and augment the existing NDE inspection and focus attention on those parts that display low compressive surface residual stress being the most likely candidates to have cracks. Those disks with tensile residual stress in critical locations become candidates for immediate removal from service. The use of residual stress measurement would thus help to negate subsequent NDE misses. The addition of residual stress measurement to any Retirement for Cause program such as ERLE will aid in differentiating disks with remaining life from those whose life is exhausted.

However, much work is yet to be completed on actually tracking residual stress with cycles and time at operating conditions. It is imperative to treat this data as one would any material characterization. As the database is collected for all materials, it is anticipated that we will be able to determine a minimum value of compressive residual stress, which is necessary to make the next inspection interval. It is also hoped that we would be able to determine a value associated with abusive peening (too high of a compressive residual stress). These measures only tell about the surface condition and would complement other techniques such as EC and ultrasonic surface/near surface inspections.

A further effort is being conducted to determine if there is a relationship or rather a correlation to the subsurface Stress State of the hardware. In other words, do the internal areas of the rotors degrade in stress levels/capability in a corollary fashion to the surface areas? This will take much longer to determine and may yield nothing. In the foreseeable future, ultrasonic inspections for internal cracks are the only reliable method of determining the internal health of the rotors.

Short Term Extension through Risk Management

Another method of life extension that has been used in several instances is called total life. Total life is defined as: (-3σ) LCF + (-3σ) crack propagation. This extension methodology is only used for small controlled populations when it is necessary to use a risk

management philosophy due to extenuating circumstances (i.e. lack of parts). The USAF doesn't recommend or use this practice for long term life extension, such as Retirement-for-Cause.

Summary

In summary, many existing technologies can be used to extend the life of rotating hardware. These extensions will result in millions of dollars worth of savings while maintaining risk at current levels established during the normal LCF life. Many of theses can be done today. We have use of damage tolerant methodologies. We have state of the art inspection systems. However, there are still some holes, such as a new inspection system to look for cracks in the bores and webs of disks. Even with these, I believe we need to take conservatism out of our designs while maintaining the present risk level. This means we need to optimize our designs. It is imperative to pursue future technology advancements to provide longer extensions at reduced risk levels. The highest cost in these technologies is not the technology, but the true validation of the technologies based on our failure history and present inherent risk levels.

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